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INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 6 :
G05F 1/32, H02J 3/01, 3/12, H02H 9/02

A1

(11) International Publication Number: WO 97/34210

(43) International Publication Date: 18 September 1997 (18.09.97)

(21) International Application Number: PCT/SE97/00424

(22) International Filing Date: 13 March 1997 (13.03.97)

(30) Priority Data:
9600988-1 15 March 1996 (15.03.96) SE

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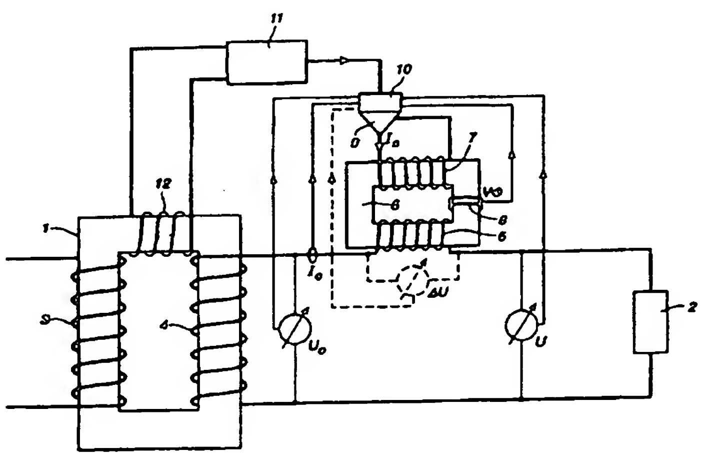
(81) Designated States: CN, JP, US, European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.
In English translation (filed in Swedish).

(54) Title: CONTROLLABLE REACTOR WITH FEEDBACK CONTROL WINDING



(57) Abstract

A device for performing, individually or in combination with each other, the functions of voltage control, power factor correction, current limiting and harmonic filtering at a network, with a line voltage U_0 and a load voltage U, with the aid of a control voltage ΔU. The device comprises a controllable reactor comprising at least one control winding (7) and at least one power winding (5) for generating the control voltage ΔU, as well as a control unit (10) which, via at least one power amplifier (9), delivers a control current I_s to the control winding. The power winding is connected in series with the load (2) and through it flows a load current I_0. A measuring member (8) senses the magnetic flux (Φ) of the controllable reactor and delivers a flux voltage $V\Phi$ proportional thereto. Via measuring members, those signals which correspond to the line voltage U_0, the load voltage U, the control voltage ΔU, the load current I_0 and the flux voltage $V\Phi$ are fed back to the control unit which, in dependence thereon, via the power amplifier(s), delivers such a control current I_s to the control winding that the control voltage ΔU induced in the power winding supplements the line voltage U_0 such that the relevant functions or function are/is achieved.

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Controllable reactor with feedback control winding

TECHNICAL FIELD

The present invention relates to a device comprising a controllable reactor by means of which the voltage, phase, current, harmonic content, etc., of an ac network may be influenced. The controllable reactor comprises a power winding and a control winding which surround the same magnetic flux. The device also comprises a control and supply circuit for the control winding.

BACKGROUND ART, THE PROBLEM

During transmission of electric energy by means of alternating current, in a plurality of situations a need of correcting the voltage, the phase, the current and the harmonic content arises. Typical examples are:

Voltage control: The voltage is to be adjustable upwards or downwards, or the voltage is to be kept constant during varying loads;

Power factor correction: The phase position between voltage and current is to be changed;

Current limiting: The current is to be limited when exceeding a predetermined value;

Harmonic filtering: Currents with a frequency different from the fundamental of the alternating voltage, also current pulses, are to be damped.

For low voltages and currents this can be easily achieved in many different ways, often with the aid of electronics. However, technical solutions which function satisfactorily in

the low-voltage field can seldom be used directly for voltages and currents which are typical of electric energy transmission. The amount of energy which is released during a control operation would lead to rapid wear of components included in the equipment, and the locally high electric field strength may lead to electrical breakdown of insulating material. For example, the rotary transformer, which serves as a simple, robust and practically stepless voltage control for low voltage, is no alternative for voltage control of power transformers. In that case, a voltage control is achieved with on-load tap changers which make it possible to choose between a number of terminals of the control winding of the transformer. On-load tap changers are mechanically complicated designs and cause a large part of the transformer breakdowns.

Power factor correction require controllable inductances or capacitances. Also here, the solutions of the low-voltage field, for example rotary variable capacitors as controllable capacitances, cannot be used. What is chosen is instead a step-by-step connection or disconnection of inductances or capacitances with the aid of circuit breakers and/or power electronics. To be able to control with small steps, a large number of connection units, for example circuit breakers, are needed.

Harmonic filtering may be performed with permanently installed filter circuits, or with stepwise connection or disconnection of filter elements in the same way as described above for power factor correction. Also active filtering with feedback and use of power electronics occurs within some special fields of use.

Current limiting is carried out either by directly breaking the current, for example with a circuit breaker, or by placing a device in the circuit, which functions as a variable impe-

dance, for example an inductance which may be changed by changed premagnetization of the core.

Although the control cases mentioned above have one common feature, namely, to add to a given current/voltage a correcting current/voltage, solutions according to the prior art require specifically designed equipment. If only one frequency is considered, it is a question of addition of complex current and voltage values. Power factor correction and voltage control are two special cases of this addition.

SUMMARY OF THE INVENTION

A device according to the invention solves the problem of carrying out, in a stepless manner, voltage control, power factor correction, harmonic filtering and current limiting using one and the same piece of equipment. By combining a conventional on-load tap changer with at least one device according to the invention, the problem with arcing arising in the on-load tap changer can be considerably reduced and voltage levels between the positions of the on-load tap changer be chosen continuously.

A device according to the invention will normally be used in connection with a network, the line voltage U_0 of which is to be supplemented with a control voltage ΔU before it reaches to a load which places high demands on the feeding voltage, referred to below as load voltage U. Normally, the load is a network comprising a number of load objects. By being able to combine voltage control, power factor correction and harmonic filtering, a device according to the invention may maintain the load voltage with unchanged amplitude, phase shift between voltage and current and harmonic content even if the load contains greatly varying resistive, reactive and non-linear loads. Upon exceeding a fixed maximum current to the load, the device may, in addition, limit this current.

For each phase of the network, a device according to the invention comprises at least one control winding and at least one power winding with a common magnetic flux Φ which is measured with a transducer, preferably a measuring coil surrounding the same magnetic flux. The current I_0 through the power winding and the load, referred to below as a load current, the line voltage U_0, the load voltage U and the voltage across the power winding which constitutes the above-mentioned control voltage ΔU are measured with the aid of suitable measuring means and are supplied to a control unit together with a signal corresponding to the magnetic flux, for example the voltage of the measuring coil, referred to below as the flux voltage $V\Phi$. The control unit controls a power amplifier which supplies the control winding with a control current I_s. The relationship between the measured values I_0, ΔU, U_0, U, $V\Phi$ and the control current is determined by the desired function of the device.

Depending on the phase angle of the control voltage ΔU added to the line voltage U_0, power may flow in both directions between the power amplifier and the control winding. Thus, the power source of the power amplifier must be able both to deliver and receive power. If the voltage and/or power values become too large to be handled by a single power amplifier, the control winding may instead be sectioned with one power amplifier for each section and a common control unit for all the power amplifiers be used.

In its function as voltage-control equipment, the power amplifier delivers a control current which gives rise to a control voltage +/- ΔU in the power winding, depending on whether the load voltage is to be increased or decreased. In the case of power factor correction, a control voltage ΔU is instead achieved which is phase-shifted by +/- $\pi/2$ in relation to the line voltage U_0. A combination of power factor correction and voltage control means an arbitrary phase angle of the

control voltage ΔU which can also be expressed as a complex voltage which is added to the line voltage U_0.

In the function as a current limiter, a control current I_s is fed to the control winding which, for a load current I_0 through the power winding which falls below a predetermined maximum value, results in the magnetic flux Φ disappearing. Then the control voltage ΔU across the power winding is reduced to the normally negligible resistive voltage drop. This is equivalent to a transformer with a short-circuited superconducting secondary coil which becomes traversed by the secondary current which causes the magnetic flux to disappear. This method is used in the patent 94/01470-1 SE for active damping of magnetic fields. If the load current I_0 exceeds the maximum value, the control current is no longer increased in a corresponding way but is maintained at a value corresponding to the maximum value. This means that the magnetic flux Φ becomes different from zero. For a load current I_0 through the power winding which exceeds the maximum value, a device according to the invention functions as a reactor which limits this current by achieving an inductive voltage drop across the power winding. By subsequently reducing the control current I_s to zero, the device functions as a current-limiting reactor with a considerable inductance.

In the function as a harmonic filter, the control winding is fed with a control current which only contains the fundamental of the line voltage with a current intensity which is so adapted that the fundamental component of the magnetic flux disappears. The load current through the power winding then only "sees" one, in practice negligible, resistive load for the fundamental, but an inductive load for all the harmonics and also other disturbances, for example current pulses. A device according to the invention is thus made to function as a bandpass filter with the fundamental frequency as the centre frequency. The control unit may also be caused to give a con-

trol current in opposition to current components through the power winding which do not belong to the fundamental; the device then functions as an active filter.

With a device according to the invention, it is possible to carry out the functions individually as described above. By Fourier series expansion of the control current I_S and superimposing selected frequencies on the control winding, it is furthermore possible to simultaneously carry out the functions in an optional combination with each other by controlling the different Fourier components of the control voltage ΔU with the Fourier components of the control current I_S. It is thus possible, for example, to carry out voltage control as well as power factor correction on the fundamental of the line voltage U_0 while simultaneously carrying out harmonic filtering on the other frequency components.

The invention may be regarded as an improvement of a so-called booster transformer, where the galvanic coupling between a winding of an excitation transformer and a winding of a series transformer, which only permits voltage control, is replaced by the control unit and the power amplifier. In this way, the plurality of control functions already described may be achieved.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 shows a device according to the invention, connected to a network in the form of a power transformer and a load.

Figure 2 shows the relationship between uncorrected and corrected voltage in a vector diagram.

Figure 3 shows a non-sinusoidal line voltage, the control voltage of the device and a load voltage after filtering.

Figures 4a and 4b show schematically combinations of an on-load tap changer with one or more devices according to the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Figure 1 shows a device according to the invention, which is connected between a network in the form of a power transformer 1 and a load 2, symbolized by a resistor. The load 2 may consist of a network comprising a plurality of consumers. The power transformer has a primary winding 3 and a secondary winding 4. The voltage of the secondary winding corresponds to the above-mentioned line voltage U_0. In a preferred embodiment, the device comprises an iron core 6 with a power winding 5, a control winding 7 and a measuring winding 8 for determining the magnetic flux Φ in the iron core. The power winding is connected in series with the secondary winding and the load, and a load current I_0 flows in the circuit. The control winding is fed from a power amplifier 9 which is controlled from a control unit 10. The power amplifier and the control unit are fed with current from a current supply device 11, which in turn is fed from an auxiliary winding 12 of the power transformer 1. This has the advantage that the frequency of the power supply corresponds to the frequency of the current in the control winding, which may simplify the design of the power amplifier. The voltage supply to the current supply device may also take place directly from the primary or secondary winding of the transformer.

Via suitable measuring means, the line voltage U_0, the load voltage U, the load current I_0 and the voltage $V\Phi$ across the measuring winding, which is proportional to a magnetic flux Φ common to the power winding and the control winding, are fed back to the control unit. Since ΔU and U fulfil the equation $\Delta U = U - U_0$, also the combinations ΔU and U_0 or ΔU and U may be supplied to the control unit instead of the combination U and U_0, depending on which combination of measurements is

simplest to achieve. In that case, it is also necessary for ΔU to be measured; this is indicated in dashed lines in Figure 1.

According to the invention, the control unit is to be programmed such that, on the basis of the feedback signals and otherwise well-known relationships between these, it achieves, via the power amplifier, the control current I_S to the control winding which is needed for the control voltage ΔU to become the proper supplementation of the line voltage U_0 for the application in question. As described, the application may be voltage control of the load voltage U at varying line voltage and/or load, power factor correction, current limiting, filtering, etc., or some combination thereof.

In case of voltage control with respect to amplitude, the control voltage corresponds to the amplitude of that control error which is obtained on a comparison between the desired amplitude $|U|$ and the actual amplitude of the load voltage, that is, $|\Delta U|=|U|-|U_0|$. With access to the number of winding turns of the control and power windings and other data for the magnetic circuit, the relationship between the flux Φ for a given ΔU and the relationship between the flux Φ and the control current I_S, respectively, may be determined. This means that the control unit, via the power amplifier, may generate that control current I_S which gives a flux proportional to ΔU, in phase with or in opposition to the line voltage U_0, in the power winding.

With access to the relationship between the line voltage U_0 and that control voltage ΔU with phase +/- $\pi/2$ relative to the phase of the line voltage which is needed for a given power factor correction of the phase of the load voltage, the ΔU necessary for a desired power factor correction may be determined. The amplitude of the relevant load voltage is then determined from the relationship $|U|^2=|U_0|^2+|\Delta U|^2$. When ΔU is determined, the control unit can generate the required control

current via the power amplifier in the same way as described above.

A frequently occurring control case is that the load voltage U has to be controlled both in amplitude and in phase relative to a line voltage U_0. The task thus comprises, according to Figure 2, determining the ΔU, both from the amplitude and the phase point of view, which is needed for the vectorial sum of U_0 and ΔU to correspond to the desired load voltage U. If the desired load voltage U is phase-shifted by an angle φ relative to the line voltage U_0, the amplitude of ΔU is determined according to

$$|\Delta U| = \sqrt{((|U|\cos\varphi - |U_0|)^2 + (|U|\sin\varphi)^2)}$$

and the phase shift α between ΔU and U_0 is determined from

$$\alpha = \arctan((|U|\sin\varphi)/(|U|\cos\varphi - |U_0|))$$

With ΔU determined in this way, the control unit may generate the required control voltage via the power amplifier, in the same way as described above.

When a device according to the invention is to function as a current limiter, it is a precondition that, at a load current I_0 less than an allowed maximum current I_{0max}, it shall have as small an influence on the circuit as possible. The control unit is therefore adapted such that, at a load current less than the maximum current, it generates and adapts such a control current I_s that the resultant flux from the control winding and the power winding is zero. This means that, at maximum load current I_{0max}, there is a corresponding maximum control current I_{smax}. At zero flux, the control voltage ΔU across the power winding will consist of the normally negligible resistive voltage drop caused by the relevant load current and the resistance of the power winding.

In a preferred embodiment as a current limiter, during a transition stage after the load current has exceeded the maximum current, the control unit is adapted to maintain the maximum control current I_{smax}. Because the load current becomes greater than I_{0max}, during the transition stage the flux will become different from zero which means that the circuit will have a limited addition of inductance. By reducing the control current to zero after the transition stage, which may amount to some twenty or thirty milliseconds, the device will function as a current limiting reactor with a considerable inductance.

In an alternative embodiment as a current limiter, the reduction of the control current may take place immediately after the load current tends to exceed the maximum current, that is, the above-mentioned transition process is excluded.

The principle of the use of a device according to the invention as an active filter is clear from Figures 3a, b and c. Figure 3a shows a non-sinusoidal line voltage U_0 as a function of time t. The control unit is arranged with a Fourier filter which produces the sinusoidal fundamental component of the line voltage and forms that control voltage ΔU, shown in Figure 3b, which corresponds to the difference between the relevant line voltage and its sinusoidal fundamental component. With access to the necessary control voltage ΔU, in the same way as above, that control current I_s may be generated which, via the power amplifier, gives a flux in the power winding proportional to ΔU.

When using the device as a passive filter for the fundamental component of a line voltage, the control voltage ΔU is to correspond to the fundamental component and the amplitude of the line voltage, which may both be extracted from the above-mentioned Fourier filter. In the same way as above, also in this case that control current I_s may be generated which, via

the power amplifier, gives a flux in the power winding proportional to ΔU.

Figure 4a and Figure 4b show schematically how at least one device according to the invention may be used for stepless voltage control together with an on-load tap changer of a power transformer or a reactor. In Figure 4a the terminals of an on-load tap changer are symbolized by the rings 13. The voltage step between two terminals is δU. Two consecutive terminals, each with a respective device according to the invention, symbolized by the coils 14 and 15, are connected to the point 16, where the voltage may be varied in a stepless manner between the voltage of the two terminals by the lower device 15 delivering a control voltage $\Delta U_1 = a\delta U$ and the upper device a control voltage $\Delta U_2 = (a-1)\delta U$, with $0 \leq a \leq 1$. In Figure 4b, one of the devices is replaced by a direct connection 17 which is only connected when the device 16 provides the same control voltage ΔU as the voltage step δU between the terminals, such that the point 16 and the upper terminal lie on the same voltage.

Also other connections between an on-load tap changer and at least one device according to the invention are feasible.

Connecting an on-load tap changer in this way to at least one device according to the invention entails several advantages:

Contacts may be opened and closed in a voltage-free and hence discharge-free manner;

The voltage of a power transformer or a reactor may be controlled in a stepless manner;

The on-load tap changer may be designed with fewer terminals.

A device for control of the voltage of the power transformer need only be dimensioned for one voltage step between the terminals.

In addition to the examples stated above, closely related fields of use as well as combinations thereof may be used within the scope of the invention. Thus, for example, a device according to the invention may be used at the same time for both power factor correction and filtering.

CLAIMS

1. A device for performing, individually or in combination with each other, the functions of voltage control, power factor correction, current limiting and harmonic filtering at a network, with line voltage U_0, for feeding a load (2), which may comprise a plurality of consumers, with a load voltage U, with the aid of a control voltage ΔU and wherein the device comprises a controllable reactor comprising at least one control winding (7) and at least one power winding (5) for generating the control voltage ΔU, as well as a control unit (10) which, via at least one power amplifier (9), delivers a control current I_s to the control winding, and wherein the power winding is connected in series with the load, and wherein a load current I_0 flows through the power winding and the load, and wherein a measuring member (8) is adapted to sense the magnetic flux (Φ) of the controllable reactor and to deliver a flux voltage VΦ proportional to the magnetic flux, **characterized** in that, via measuring members, those signals which correspond to the line voltage U_0, the load voltage U, the control voltage ΔU, the load current I_0 and the flux voltage VΦ are fed back to the control unit which is programmed such that, on the basis of the feedback signals, it delivers via the power amplifier(s) such a control current I_s to the control winding that the control voltage ΔU induced in the power winding supplements the line voltage U_0 such that the relevant functions or function are/is achieved.

2. A device for voltage control according to claim 1, **characterized** in that a control error arisen during voltage control constitutes a control voltage ΔU and that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_s which provides a magnetic flux Φ, proportional to ΔU, in phase with or in opposition to the line voltage U_0, such that $U_0 + \Delta U = U$ corresponds to the desired load voltage U.

3. A device for power factor correction according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S which corresponds to a magnetic flux Φ, which results in a control voltage ΔU which is phase-shifted relative to U_0 by $+/- \pi/2$, such that the voltage amplitudes, symbolized by $| \ |$, fulfil the equation $|U_0|^2 + |\Delta U|^2 = |U|^2$ where U is the desired load voltage.

4. A device for voltage control and power factor correction according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S which corresponds to a magnetic flux Φ, which results in a control voltage ΔU which has such a phase and amplitude that the load voltage U is given a desired amplitude $|U|$ and a desired phase shift φ towards the line voltage U_0.

5. A device for current limiting according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S to the control winding which, for a load current I_0 through the power winding which falls below a given maximum value I_{0max}, results in the magnetic flux Φ disappearing but which for a load current I_0 which exceeds the given maximum value does not exceed the corresponding maximum value I_{smax} of the control current and where the same control current I_S within a few tens of milliseconds drops to zero.

6. A device for current limiting according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S to the control winding which, for a load current I_0 through the power winding which falls below a given maximum value, results in the magnetic flux Φ disappearing but where the same control

current I_S for a load current I_0 which exceeds the given maximum value is immediately reduced to zero.

7. A device for passive harmonic filtering according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S which only contains the sinusoidal fundamental component of the line voltage and that the amplitude of the control current is such that the fundamental component of the magnetic flux disappears.

8. A device for active harmonic filtering according to claim 1, **characterized** in that the control unit (10), via the power amplifier (9), is adapted to generate a control current I_S which only contains the sinusoidal fundamental component of the line voltage, that the amplitude of the control current is so great that the fundamental component of the magnetic flux disappears and that the control current, in addition, contains the harmonics of the load current I_0 in opposition.

9. A device according to any of claims 1 to 8, **characterized** in that the control winding is sectioned into part-windings.

10. A device according to claim 9, **characterized** in that a power amplifier (9) is arranged for each part-winding of the control winding.

11. A device according to any of claims 1 to 4, **characterized** in that it is arranged together with at least one on-load tap changer of a power transformer or a reactor for voltage control between the terminals (13) of the on-load tap changer.

12. A device according to any of claims 1 to 11, **characterized** in that the device is arranged adjacent to a power transformer (1).

13. A device according to claims 12, **characterized** in that the power supply to the power amplifier (9) takes place with at least one auxiliary winding (12) of the power transformer (1).

14. A device according to claims 12, **characterized** in that the power supply to the power amplifier (9) takes place from the primary or secondary winding of the power transformer.

15. A device according to any of claims 1 to 14, **characterized** in that the control winding and the power winding are wound on a common core (6) of magnetizable material.

Fig. 1

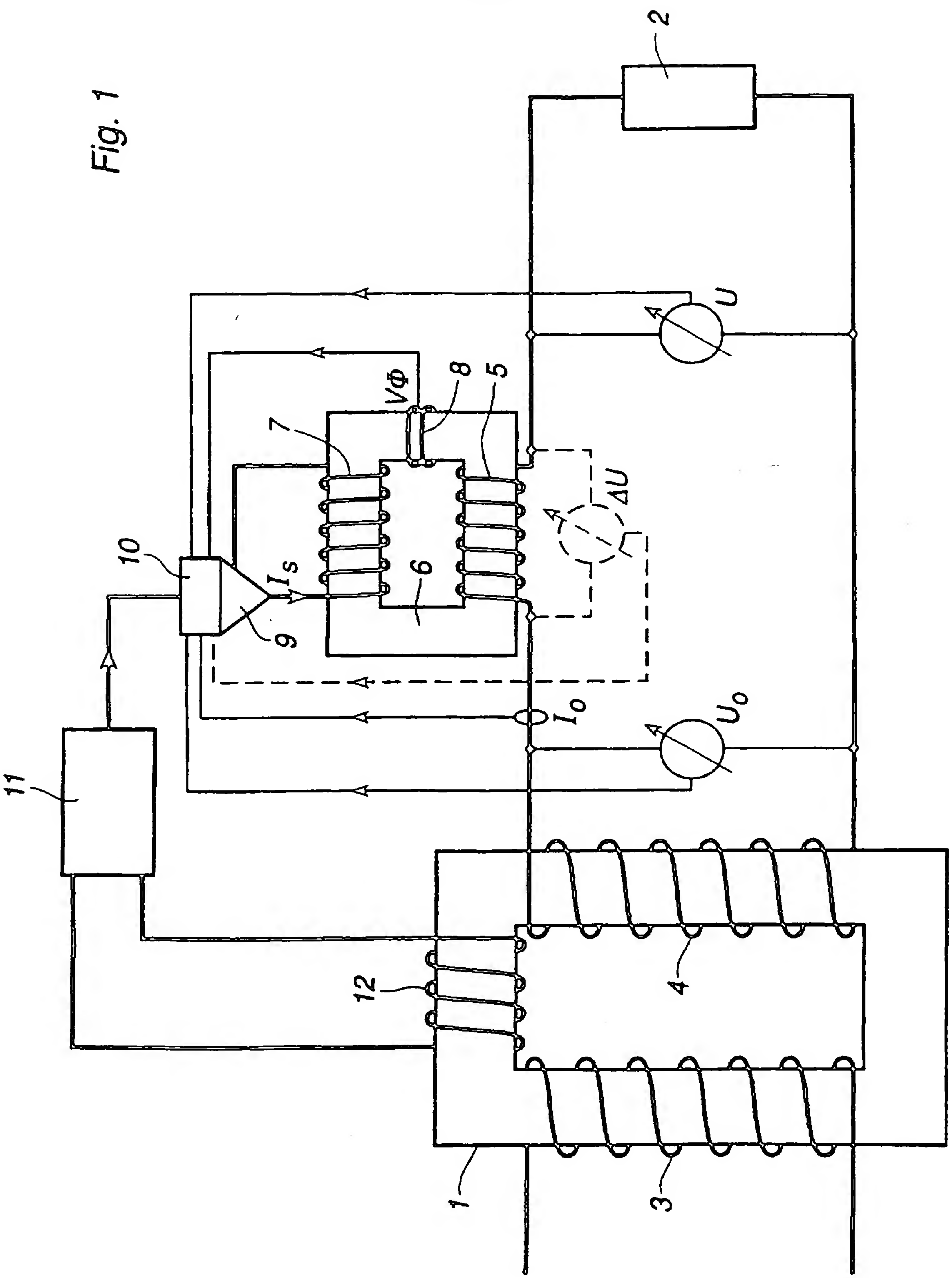


Fig. 2

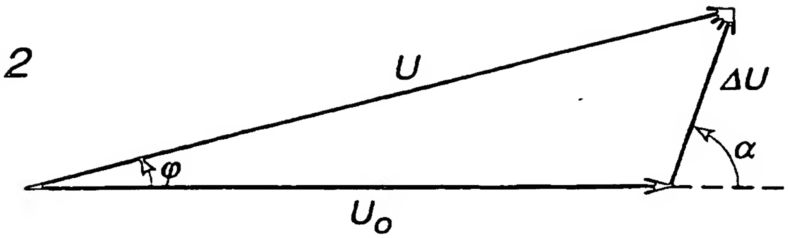


Fig. 3

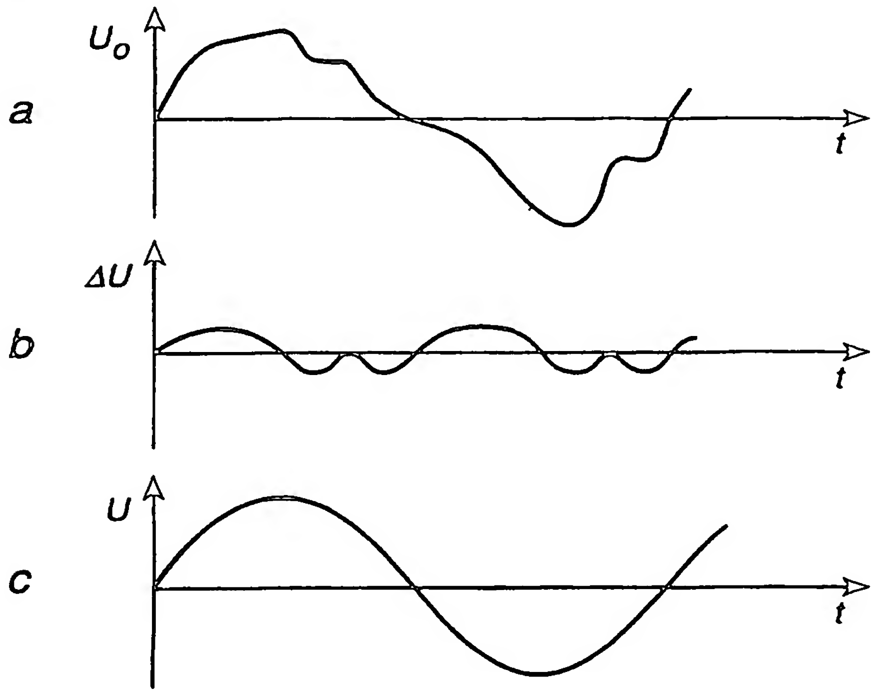


Fig. 4a

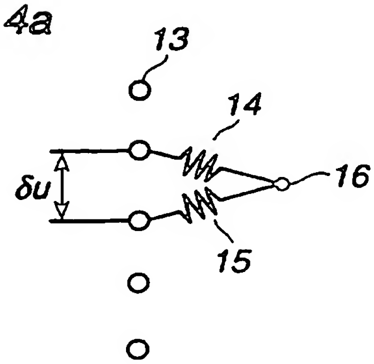
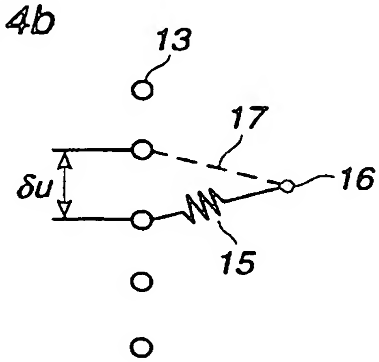


Fig. 4b



INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 97/00424

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: G05F 1/32, H02J 3/01, H02J 3/12, H02H 9/02
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: G05F, H02J, H02H

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	DE 1513876 A (HONEYWELL INC.), 18 Sept 1969 (18.09.69), page 1, line 1 - page 2, line 7 --	1
A	Patent Abstracts of Japan, Vol 13,No 444, E-828, abstract of JP,A,1-170328 (NISSIN ELECTRIC CO LTD), 5 July 1989 (05.07.89) --	1
A	US 4833585 A (S. MORAN), 23 May 1989 (23.05.89), column 1, line 44 - column 2, line 2 --	1
A	US 5341281 A (G. SKIBINSKI), 23 August 1994 (23.08.94), abstract --	1

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
17 June 1997	28.06.97
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INTERNATIONAL SEARCH REPORT

International application No.
PCT/SE 97/00424

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